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MENTS ON FOUR DIFFERENT TECHNIQUES FOR AUTOMATICALLY LOCATING LAND VEHICLES
A Summary of Results

Bernard E. Blood
Bernd W. A. Kliem

U.S. DEPARTMENT OF TRANSPORTATION
Transportation Systems Center
Kendall Square
Cambridge MA 02142

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16. Abstract

During the winter of 1976-77, four different technical methods for automatically locating surface vehicles were tested in both high and low-rise regions in Philadelphia PA. The tests were designed to evaluate the methods for their applicability as location subsystems for Automatic Vehicle Monitoring systems. Two "signpost" concepts, one utilizing semi-passive transponders and the other active transmitters, as well as two "area-coverage" concepts, one employing Loran-C and the other a pulse trilateration method, were tested. A summary of results and major findings are presented.

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PREFACE

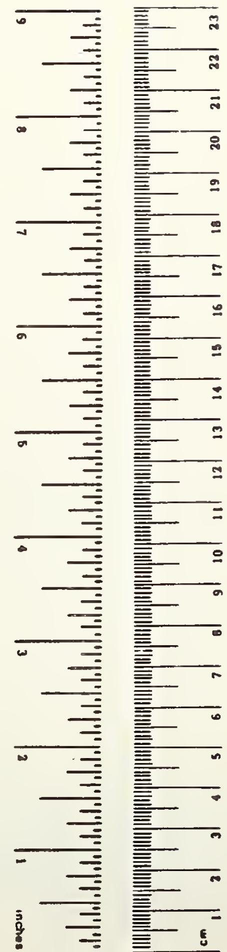
The experimental work summarized in this report was carried out in Philadelphia by Fairchild Space and Electronics Company, Hazeltine Corporation, Hoffman Information Identification, Inc., and Teledyne Systems Company, each under separate contract to the U. S. Department of Transportation, Transportation Systems Center (DOT/TSC). The research was sponsored by the Urban Mass Transportation Administration (UMTA) and represents the first phase in a program to develop and deploy an Automatic Vehicle Monitor (AVM) system. The Phase I objective was to formally test four different vehicle-location concepts against a technical performance specification prepared by TSC. Phase II of the AVM program will involve the selection of one of the tested location methods, the detailed design of an overall AVM system, and its deployment in a major urban area for test and evaluation in bus-transit and police operations.

The directors of the Philadelphia tests were Messrs. B. Kliem, J. Herlihy and R. Ow and, in addition, Messrs. P. Segota and P. Mengert provided data analysis support. Corroborative processing of raw test data was carried out at the MITRE Corporation under the direction of Mr. J. Ludwick, Jr. Mr. D. Symes, the UMTA program manager for AVM, provided overall program direction.

METRIC CONVERSION FACTORS

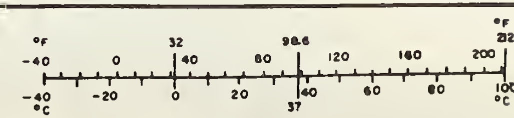
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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1. INTRODUCTION

During the winter of 1976-77, four different technological methods for automatically locating land vehicles were tested in both high and low-rise regions in Philadelphia, Pennsylvania. The four test systems were developed, manufactured and operated by the following companies:

Fairchild Space and Electronics Company
Germantown, Maryland

Hazeltine Corporation
Greenlawn, New York

Hoffman Information Identification, Inc.
Ft. Worth, Texas

Teledyne Systems Company
Northridge, California

The tests were designed and directed by the Transportation Systems Center(TSC) under the sponsorship of the Urban Mass Transportation Administration (UMTA).

This report outlines the experimental objectives, summarizes the test results and presents major findings. As detailed accompaniments, Final Reports from the companies give, in each case, system design details, complete test data and an assessment of what was learned in the tests that would lead to design corrections or improvements (Refs. 1, 2, 3, 4).

2. EXPERIMENTAL OBJECTIVES

2.1 BACKGROUND

As one element in its overall program to develop and deploy new technologies for the improvement of urban transportation, UMTA has sponsored research on Automatic Vehicle Monitor Systems (AVM) as an evolving technology that offers considerable potential in the near term for improving levels of service and, at the same time, reducing operating costs in bus-transit systems. In this context, AVM is a terminology for a class of electronic systems that, through automatic position-tracking and status-monitoring, provide the information as well as the means for central control of individual vehicles in a fleet dispersed over an operating area. Such systems are considered to be comprised of three functional elements: a location subsystem to provide continuous position tracking of each vehicle; a communications subsystem to monitor vehicle status and to return control commands to the vehicle; and a computer subsystem to manage the information flow, process incoming data, generate displays to a dispatcher and prepare records for subsequent analysis.

Of the three functional elements, the location subsystem is the critical technical development. It not only characterizes the AVM system design, it is the primary factor in deployment costs. Furthermore, with the parallel applications of AVM for police, paratransit, and commercial vehicle fleet, as well as for bus-transit, it becomes important to consider development of multiuser location subsystems--serving both random and fixed-route fleet operations. The benefits of multiuse that might be derived are reduction in aggregate capital costs, efficient use of the radio spectrum and development of a common technology with the resulting economies of scale.

In 1975, to further the development as well as to refine and demonstrate multiuser AVM application, UMTA and TSC initiated a two-phase program:

1. The test and evaluation of several candidate location subsystem concepts--one to be selected for a multiuser AVM system design.

2. The design and development of a multiuser AVM system, its deployment in a large urban area and the quantitative evaluation of its effectiveness in fixed-route bus-transit and in random-route fleet operations.

Phase I of the program was completed in March 1977. Four different location subsystems, selected out of a range of proposals from industry, were tested against a TSC specification of the performance required for the location subsystem in a multiuser AVM system.

2.2 MULTIUSER AVM TECHNICAL SPECIFICATION

The multiuser AVM performance specifications were based on bus-transit and police operational requirements. Actual levels (e.g., location accuracy) were established to permit the demonstration of postulated payoffs (Appendix A) in operational improvements, while, at the same time, keeping these levels within the state of the art for a range of competitive location subsystem technologies.

The items of specification (Appendix B) for the location subsystem are summarized in Table 1. At the location-subsystem level, the specification, written for both fixed-route bus and random-route police car operations, refers to a single AVM-equipped vehicle for which, at any given instant, the location error is the radial distance between true position and that measured by the location subsystem. The 99.5% error specification is imposed because very large errors--even though the overall average may be reasonable--would be extremely disruptive in the control of buses or the dispatch of police cars. The maximum average error on any 0.1 mile segment of any travelway is limited to 450 feet to obtain complete coverage--i.e., elimination of isolated areas (or pockets) of no coverage or poor performance.

Since Phase II involves the development of an overall AVM system the specification also prescribes system-level performance as summarized in Table 2. At this level, the specification refers

TABLE 1 LOCATION SUBSYSTEM-LEVEL PERFORMANCE SPECIFICATION

ITEM	FIXED-ROUTE OPERATION	RANDOM-ROUTE*
95% OF ALL LOCATION INDICATIONS	ERROR < 300 FEET	
99.5% OF ALL LOCATION INDICATIONS	ERROR < 450 FEET	
MAXIMUM AVERAGE ERROR ON ANY 0.1 MILE SEGMENT	AVERAGE ERROR < 450 FEET	

*Same as Fixed Rt.

TABLE 2 AVM SYSTEM-LEVEL PERFORMANCE SPECIFICATION

ITEM	FIXED-ROUTE OPERATION	RANDOM-ROUTE OPERATION
95% OF ALL LOCATION INDICATIONS (OR UPDATES)	ERROR < 300 FEET	ERROR < 300 FEET
99.5% OF ALL LOCATION INDICATIONS (OR UPDATES)	ERROR < 450 FEET	ERROR < 450 FEET
99% OF ALL TIME-OF-PASSAGE DETERMINATIONS	ERROR < $\pm$ 15 SEC.	-----------------
99.5% OF ALL TIME-OF-PASSAGE DETERMINATIONS	ERROR < $\pm$ 60 SEC.	------------------

to a fleet of AVM-equipped vehicles for which errors of Table 2 represent the aggregate performance over any statistically significant period of time (i.e., at least the length of one full operational day for the system). System-level performance includes errors introduced by the communications system--particularly errors resulting from finite polling intervals-- but also corrective measures such as error-corrective coding as well as extrapolation of position and other data-smoothing techniques. In fixed-route bus operations, an AVM system, when used to collect run-time data for preparation of schedules or when used to monitor schedule adherence, must accurately measure the time-of-passage of buses at particular "time points" along the route. The accuracy required (Appendix A) as indicated in Table 2 is ± 15 seconds for 95% of the occurences.

As in the subsystem specification, the specification at the system-level also imposes a 99.5% error bound to limit the frequency of very large errors.

2.3 LOCATION SUBSYSTEM TEST EQUIPMENT REQUIREMENTS

For the Phase I Philadelphia tests, each of the four contractors was required to assemble and demonstrate a prototype location subsystem that was fully representative of that proposed for the overall Phase II system. The experimental equipment included the following:

a) A test-vehicle suitable for simulating both fixed-route and random-route fleet operations in Philadelphia traffic.
b) In-vehicle location-subsystem equipment that was fully representative of the proposed Phase II hardware.
c) Wayside location-subsystem elements (hardware fully representative of that proposed for Phase II) to provide coverage of specified test-routes and areas
d) Data acquisition equipment including reference systems (e.g., fifth wheel for precise indication of distance traveled) and recorders.

e) Test and calibration instrumentation.

f) Spare parts

For this equipment, then, the minimum functional requirements were to provide location-subsystem data sufficient for complete position fixes and times of passages; reference position and time-of-passage data for establishing errors; and recordings of all data against a correlatable time-base of sufficient resolution (determined by AVM performance specification).

2.4 TEST DATA REQUIREMENTS

All contractors were required to obtain sufficient data to directly establish that (or the degree to which) their location subsystems met or exceeded the specifications of Table 1. Also, the data were to be adequate for establishing--through a computer simulation--the degree to which the system-level specifications of Table 2 were met or exceeded. The minimum size of the independent-data samples were to be sufficient to determine whether or not the 95% error specifications were met to a reasonable degree of confidence. Since statistical error distributions were not known a priori, a non-parametric analysis was performed to establish recommended sample sizes (5). In this analysis, an adequate sample size was determined such that

> The probability that a "95%-system" (i.e., one that truly meets the 95% error specification) is mistakenly found non-compliant to the specification is less that 5%.
> The probability that a less than "95%-system is mistakenly found compliant to the specification is minimized.

Recommended sample sizes of about 450 limit the probability of mistakenly taking a true 95% system as non-compliant to 4%. Also, this sample size results in 5% probability that a 91% system (or a 1% probability that a 90% system) is mistakenly taken as compliant to the 95% error specification. Further significant reductions in uncertainty would have required unjustifiably large sample sizes.

To gather the data sample for evaluation of fixed-route performance, the test vehicle was required to simulate bus operations

(speed levels and stop patterns) on a specified route of approximately 15 miles in length. A different route was specified for each contractor; however, in general, all routes presented similar characteristics-- a mixture of low-and high-rise segments. Each route was marked with about 75 check points of precisely known location in geographic coordinates. As the vehicle passed these points, an event mark was manually entered on the data record. Included in each route were about 15 special time points; the event-times at each were recorded for purposes of checking system performance against the "time-of-passage" specification (Table 2). The test vehicle as a simulated bus was required to stop for short time periods at 50% of the time points-- randomly selected on any one run over the route. The route was repeatedly traversed to obtain a "time-point" sample of 450. This required approximately 30 runs. Also, these runs provided a sample size, including all check points, of about 2100 for evaluating the location subsystem position-indication performance. The same check points were used on each run; however, each run represented a significantly different case based on changes in traffic, average speed, weather and other time-of-day or day-of-week dependent conditions.

To gather the sample for evaluation of random-route performance, the test vehicle was required to simulate police car (or taxicab) average speeds while moving generally with the traffic over a route about 10 miles long, confined within a specified area. Each company was assigned a different random-route area; however, their physical characteristics were similar--each was comprised of a mixture of high-and low-rise subareas. As in the fixed-route tests the random-route was traversed repeatedly to obtain a sample at 450 check points. With about 60 check points on the route, eight runs were generally required. Again, although the location of check points remained the same, each run represented a different case as the result of time-of-day changes in conditions.

In addition to the data collected to test the location subsystems against the specifications of Tables 1 and 2, special case tests were conducted for each. Depending upon the individual

location subsystems, the following tests were required:

a) Demonstration of operation at very high speed (up to 100 m.p.h)
b) Demonstration of operation under varying levels of background-noise (electromagnetic)
c) Measurement of antenna patterns of wayside devices as deployed in different environments
d) Measurement of location-indication performance on special routes in suburban areas (generally a small sample size)

2.5 EXPERIMENTAL PROCEDURES

All official tests were conducted according to a detailed plan, prepared by each contractor and approved by the Government in response to a Government "Test Requirements" document (6). The basic stipulations for each contractor are listed below.

The actual route for simulated-bus operations was prescribed by the Government at time of contract; however, checkpoints on this route were provided by DOT/TSC only 48 hours prior to initiation of test runs.

The actual area for random-route operations was prescribed at time of contract; however, the actual route and checkpoints were provided by DOT/TSC only 48 hours prior to initiation of test runs.

All official fixed-route runs, random-route runs, and special case tests were witnessed by a DOT/TSC observer.

Duplicates of all official data (i.e., tape recordings) were conveyed to DOT/TSC and subjected to independent, corroborative processing.

All data taken on all official runs became part of the performance evaluation.

3. TEST SYSTEMS

3.1 SELECTION

From a range of concepts provided in the industry response to the DOT/TSC Request for Proposal on AVM (6), four different location subsystem concepts were selected for the Phase I tests. These test systems included two proximity concepts, one utilizing semipassive transponders--"sharp-field" signposts (in the terminology of Appendix C) and the other utilizing active transmitters--"broad-field" signposts. The other two systems selected were RF trilateration concepts, one employing Loran-C and the other a pulse trilateration method. (See Appendix C for detailed definitions of terminology.) Each of the test systems from the four companies is described below.

3.2 FAIRCHILD--SHARP-FIELD PROXIMITY

The Fairchild location subsystem utilizes a semipassive signpost and on-board vehicle equipment comprised of an interrogator and intersignpost interpolator for deriving vehicle position between signposts. The signpost is semipassive in the sense that the unmodulated RF energy (at 2.48 GHz) from the vehicle interrogator is returned by the signpost as a modulated second harmonic (4.96 GHz). Depending on signpost mounting height (15 to 25 feet), the region (along the route of travel) in which the interrogation energy is intercepted and returned is 6 to 20 feet classifying the signpost as a "sharp-field" type. The signpost digital logic assembly is powered by two C-size lithium batteries and the modulation (the signpost's unique identification, a 16-bit word preceded by 8 synchronization bits) is imposed by on-off keying. The signpost returns a complete signal every 0.01 seconds while under interrogation.

For the random-route tests, 99 signposts were deployed over roughly a 50-square block area. All signposts were mounted so as to be interrogated from the right side of the vehicle and many one-way streets in the designated area permitted a reduction in the number of signposts needed. For random-route operations, the

inter-signpost interpolator consisted of an odometer and a steering angle sensor (to account for turns between signposts). Distance and direction (i.e., a vector) from the last signpost were calculated by an on-vehicle microcomputer.

For the fixed-route tests, 67 signposts were deployed along the 11.4 mile DOT/TSC designated route. The average spacing of signposts was 900 feet with a maximum of 2450 feet. The steering angle indicator was not used; however, the odometer--zeroed at each signpost--indicated the distance traveled from the last signpost. A signpost was mounted at each of the 14 time points on the route and time of passage was determined by the time at which the signpost was properly decoded (when two out of three returns gave the same code).

3.3 HAZELTINE--PULSE TRILATERATION

The Hazeltine location subsystem determines vehicle location by measuring at three fixed receiver sites the arrival times (TOA's) of a sharp rise-time pulse emitted by the vehicle on a 908 MHz carrier. These TOA's are coded and transmitted on low-bandwidth telephone lines to a central computer which calculates vehicle position by trilateration--ie., differences in TOA's for any pair of stations establishes a hyperbolic line-of position (LOP) and the intersection of LOP's gives the position fix. For the test system, the TOA's were recorded at central for off-line processing.

The test system used a basic repetition rate of two seconds which was divided into 1000 time slots each 2 ms in duration. In the first time slot, a synchronization signal(904.5 MHz) was transmitted from central control to the vehicle. The signal triggered a clock in the vehicle which then provided 20 sequential transmissions at 100-ms intervals in the time slots: 3, 53, 153, etc. In the second time slot, a calibration signal (908 MHz) was transmitted from central control to the fixed receiver sites (to calibrate their clocks for TOA measurements). In general, for a system involving many vehicles, a particular 2-ms time slot in a repetition cycle is assigned to each vehicle. The first millisecond of the slot is reserved for messages from central to that

vehicle; for example, in the test system the first half of the third time slot was used to transmit a time signal to calibrate the clock for the vehicle test data recording system. In the second half of the time slot, the vehicle transmits its location pulse followed by a vehicle to central message. It is to be noted that the Hazeltine location subsystem was unique among those tested in the sense that the communication subsystem--both central-vehicle and vehicle-central links-- was an inherent part of that system.

For the random and fixed-route tests, four receiver sites were established such that test routes were within two triangles established by these receiver locations. For the same point, this permitted the comparison of position fixes made with receivers of different separations--a maximum of 6.5 miles in one triangle and 4.6 miles in the other. The central high-rise area of Philadelphia fell within both triangles. The central sychronization transmitter and data acquisition recorders (for the TOA's from the receiver sites) were located at one of the receiver sites. Following the official tests, Hazeltine established a fifth receiver site in the central part of the high-rise area to gather additional performance data on those segments of the test routes that laid in the high-rise region.

For the fixed-route tests, Hazeltine deployed low-power signposts at all 15 time points to establish time-of-passage. Hazeltine incorporated these signposts to meet the ± 15 second specification for very slow-moving vehicles. These battery-powered signposts transmit (at 0.17 second intervals) a special signpost-code (the same for all signposts) on a 904.5 MHz carrier--the vehicle receiver "listens" for these transmissions during the second half of the time slot. By using a special antenna arrangement, a narrow angle detection region (notch) is created. When a signpost is detected, the next vehicle-central message indicates this event. The identification of a signpost is inferred from the trilateration location information.

3.4 HOFFMAN--BROAD-FIELD PROXIMITY

The Hoffman location subsystem employs a lithium-battery-powered, 49.86 MHz signpost that broadcasts at approximately 0.67 second intervals a unique 16-bit code (34-bit message with error coding) corresponding to that signpost's geographic location.

For random-route tests, 41 signposts were deployed (which created 194 location regions), generally, at every other intersection in the specified coverage area of approximately 40 square blocks. Radiation fields from adjacent signposts were adjusted to overlap so that the vehicle receiver could determine position at any point between any pair of signposts by comparing their relative signal levels. By this means, each pair of signposts established five distinct location regions: "level-one" regions immediately around the signposts; two "level-two" regions in which one or the other signal levels was greater; and a "level-three" region in which the signal levels were approximately equal. One hundred ninety-four such regions were established, the center of each was determined and recorded in geographic coordinates. In general, signpost spacing was such that no location region was longer than the location-error specification.

For the fixed-route tests, fifteen signposts were located at the DOT/TSC- designated time points which were established at about one-mile intervals. An odometer, zeroed at the passing of each of these time points, then provided the incremental distance since the last signpost. For the fixed route, the "level-one" boundaries of the signpost located (by measurement) in geographic coordinates were then used as the reset points for the odometer.

3.5 TELEDYNE--LORAN-C

The Teledyne location subsystem utilized a Teledyne commerical Loran-C receiver (Micro Locator) that was configured for operation on land vehicles. The on-vehicle system was comprised of the Loran receiver, a precision odometer, and an "augmentor " receiver. The augmemtors were low-power 70 MHz signposts deployed in regions of poor Loran-C reception-- principally in the vicinity of high-rise structures. Each augmentor (a "broad-field" type signpost) broadcasts a unique identification by means of time code; that is, identification is established by the elapsed time between start

and stop pulses. For the signpost with the longest duration code, broadcasts of identification occured approximately 12 times per second. Receipt of an augmentor (signpost) signal takes precedence over the Loran-C position indication. Prior to the official tests, Teledyne surveyed the general test area to determine the regions that would require augmentors. The survey also calibrated the Loran-C grid by measuring the Loran-C coordinates (time differences, TD's, between the pairs of Loran-C station signals) at specific geographic points. In all, 395 calibration points were established for an area (including the central Philadelphia high-rise) of about 4 mile^2. Normally, in a "perfect" Loran-C area, where the TD gradient is smooth, only 4 calibration points would be needed; however, the larger number of points is required in urban areas to account for the considerable distortions of the grid and, in some regions, severe anomalies which frequently occur in high-rise areas. Once established, the calibration information was used in the system software in converting test measurements to geographic coordinates.

In Philadelphia the Loran-C is provided by the U.S. East Coast Chain with its master station at Cape Fear, North Carolina, and slaves at Dana, Indiana, and Nantucket Island, Massachusetts. The Dana, Indiana, station supplies a very weak signal, however, which would not be representative of the general case. For this reason, the Dana signal was not used and a temporary mini-station was installed in Limerick, Pennsylvania--about 40 miles west of Philadelphia. The power level of this station was adjusted so that the Signal-to-Noise Ratio (SNR) in mid-Philadelphia was about +4 db--approximately what would be expected in Los Angeles when using the West Coast chain in Phase II. Subsequent measurements on the West Coast Chain have shown that field strength is approximately +4 db over what was expected.

For the fixed-route tests, 15 augmentors were deployed at each of the 15 time points on the 15-mile route which ran into and out of the high-rise area. Time-of-passage at the time points was determined by adjusting the augmentor field patterns such that the initial detection (i.e., three successive identical decodes) of an augmentor was at approximately 54 feet from the time point.

The odometer was then used to count down a standard distance of 54 feet to the time point.

For the random-route tests, 38 augmentors were deployed over the region which contained the DOT/TSC designated test route.

3.6 POSITION CALCULATION (TEST SYSTEMS)

For all test systems, the actual calculation of location in geographic coordinates was performed off-line using data recorded during test runs. The software programs used were, in all cases essentially those that would be part of the computer subsystem as proposed for the Phase II AVM system.

Fairchild's raw-data types, as recorded on the vehicle during test runs, included the following information, recorded as a function of elapsed time at 0.5 second intervals.

- Code of the last signpost passed.
- Current vector position with respect to last signpost (random-route tests).
- Current odometer reading (fixed-route tests).
- Event marker for system-indicated time-of-passage at time points (fixed-route tests).

Also, the following reference data (for calculating errors) were recorded on the tapes.

- Event markers for and codes of checkpoints and time points as they were passed (manually entered by the test conductor).
- Current accumulated distance traveled as measured by a special "fifth-wheel" odometer.
- Current heading.

Hazeltine's raw data were recorded at the central transmitter station and on the vehicle. The elapsed-time bases on these two tapes were synchronized by using the central-vehicle communications link as described in 3.3 above. At the central site the data were recorded at 0.1 second intervals and included

- Times of Arrival of location pulses (TOA's) as measured at the fixed receiver sites and relayed to the central site on the dedicated telephone lines.

Event markers--signpost decode--for system-indicated passage of time points. This was transmitted as part of the message from the vehicle via the fixed sites to central.

On the vehicle the following reference data (for calculating errors) were recorded at 0.1 second intervals.

Event markers for and codes of check points and time points as they were passed (manually entered by the test conductor).

Current accumulated distance traveled as measured by a special "fifth-wheel" odometer.

Hoffman's raw-data tapes as recorded on the vehicle included the following information, recorded at 0.5 second intervals.

Identifiers for current location region (see 3.4 above) in random-route tests

Code of last signpost passed (fixed-route texts).

Current odometer reading (fixed-route tests).

Also the following reference data (for calculating errors) were recorded on the tape.

Event markers for and codes of check points and time points as they were passed (manually entered by the test conductor)

Current accumulated distance traveled as measured by a special "fifth-wheel" odometer.

Teledyne's raw-data tapes, as recorded on the vehicle, included the following information, recorded at 1.0 second intervals.

Current Loran-C time difference (TD's see Appendix C).

Code of next to last augmentor passed.

Code of last augmentor passed.

Current odometer reading (increment from last recording).

Also the following reference data (for calculating errors) were recorded on the tape.

Event markers for and codes of check points and time points as they were passed (manually entered by the test conductor).

Current accumulated distance traveled as measured by a special "fifth-wheel" odometer.

Prior to the reduction of any official data tapes, each contractor submitted to DOT/TSC the complete software for reducing the position and time-of-passage data as well as the software for calculating the error statistics. DOT/TSC subsequently used this software (without revisions) to process duplicates of the raw-data tapes. The results of this processing were used to corroborate the test results as submitted by each of the contractors.

4. SUMMARY OF TEST RESULTS AND MAJOR FINDINGS

4.1 PRESENTATION OF DATA

In the following paragraphs the test results are presented in tabular form for each of the location subsystems. In all cases, the first columns represent the test results to be compared to the DOT/TSC specification. The official results are based on the data samples comprised of all measurements from official runs. Other columns in the tables represent results based on edited data or on data taken in addition to that from official runs. Data eliminated in the editing were those that were

a) Contaminated by fully identified external factors (as verified by the DOT/TSC test monitor); e.g., failures in the data acquisition system;

b) Poor due to fully identified location subsystem malfunctions or problems that were subsequently corrected or are correctable with simple design revisions.

The official results then reflect not only the capabilities of the location subsystem but the overall Phase I test system, including the data acquisition system and data reduction software. Edited data results more nearly represent the performance levels that would have been achieved had the overall Phase I test system performed optimally or had the system deployment been optimal. These edited data results are not speculative--they are based on actual data taken; yet, they do not necessarily represent the ultimate performance achievable with the location subsystem technologies tested. In this sense, these results are then indicative of the maturity of the engineering development of each of the concepts. In their Final Reports on Phase I (1,2,3,4), each of the contractors discusses the lessons learned and indicates what engineering changes could be considered for enhanced performance.

4.2 FAIRCHILD TEST RESULTS

Table 3 presents the test results for the Fairchild sharp-field proximity location subsystem. The edited-data column reflects the elimination of poor data that resulted from the lack of a "reasonableness" algorithm for rejecting nonexisting signpost codes and for rejecting signpost codes that would imply impossible vehicle speeds.

4.3 HAZELTINE TEST RESULTS

Table 4 presents the test results for the Hazeltine pulse trilateration location subsystem. The "first" column represents the test results before a correction for multipath effects. These pulse trailing edge effects persisted beyond original estimates, causing "tails" on the preamble pulses to contaminate the leading edge of the position pulse. This was subsequently corrected by a change in system timing. The second column represents results of test runs after the system timing change was incorporated to reduce the effect of multipath. The "suburban" column of results represents special test runs in the suburban, low-rise environment. The "additional data" column represents data taken with an added receiver in the high-rise test area. The edited-data colunm reflect the composite results had there been a reasonableness algorithm, map matching or projection to routes, and reduced receiver site spacing in the high-rise region.

4.4 HOFFMAN TEST RESULTS

Table 5 presents the test results for the Hoffman broad-field sign-post system. The improved time-of-passage performance in the edited-data column reflects the elimination of data obtained at the time points where the vehicle had stopped--the software system requires modification to account for this operational condition. Edited-data improvements in coverage performance resulted from the elimination of data taken when snow and ice had clogged the fifth-wheel reference, causing false indication of large errors.

TABLE 3 FAIRCHILD TEST RESULTS

DOT/TSC SPECIFICATION		
FIXED-ROUTE SUBSYSTEM LEVEL	TEST RESULTS	EDITED** DATA RESULTS
300' - 95%	57	54*
450' - 99.5%	1151	70*
SYSTEM LEVEL		
300' - 95%	82	81*
450' - 99.5%	148	125*
TIMEPOINT		
15 sec. - 95%	1	1
60 sec. - 99.5%	2	2
RANDOM ROUTE SUBSYSTEM LEVEL		
300'- 95%	250	230*
450' - 99.5%	440	440
SYSTEM LEVEL		
300' - 95%	230	220*
450' - 99.5%	440	430*
COVERAGE		
FIXED ROUTE - 99.5%	1154	120*
450' - MAX	6677	756*
RANDOM ROUTE - 99.5%	440	430*
450' - MAX	2380	623*

NOTE:

*Reflects the incorporation of "reasonableness algorithm" to reject signpost acquisition errors

**See Section 4.1 for definition of "edited."

TABLE 4 HAZELTINE TEST RESULTS

DOT/TSC SPECIFICATION	BEFORE SIGNAL TIMING CORRECTION		AFTER SIGNAL TIMING CORRECTION		SUBURBAN	ADDITIONAL DATA	EDITED** RESULTS
	△S	△L	△S	△L	△L	△S'	
FIXED-ROUTE SUBSYSTEM LEVEL							
300'@	- -	- -	81%	- -	96.6%	--	--
300' - 95%	--	--	720	1020	270	--	270-460
450' - 99.5%	--	--	4100	1720	693	--	693-940
SYSTEM LEVEL							
300'@	- -	- -	81%	69%	--	84%	--
300' - 95%	--	--	790	1780	--	460	191-325*
450' - 99.5%	--	--	3546	5757	--	940	490-665*
TIMEPOINT							
15 sec.@	- -	- -	85%	92%	92%	--	--
15 sec - 95%	--	--	39	25	21	--	15*
60 sec.@	- -	- -	98%	99%	- -		
60 sec - 99.5%	--	--	118	170	27	--	30*
RANDOM-ROUTE SUBSYSTEM LEVEL							
300' - 95%	4420	2400	1300	1260	--	--	270-460
450' - 99.5%	8838	4600	3020	>3000	--	--	693-940
SYSTEM LEVEL							
300'@	- -	- -	75%	68%	- -	72%	--
300' - 95%	>3000	1920	880	1600	--	950	270-460
450'- 99.5%	5171	3560	1960	>3000	--	1800	693-940
COVERAGE							
FIXED ROUTE 99.5%	--	--	1220	1220	560	--	693-1220
450' - MAX	--	--	1300	3331	1020	--	--
RANDOM ROUTE 99.5%	5784	2258	1605	5248	--	--	693-1220
450' - MAX	5784	2258	1605	5248	--	--	--

NOTE: *Reflects the incorporation of "reasonableness algorithm" and map matching or projection to route.

**See Section 4.1 for definition of "edited."

△S = Small Triangle

△L = Large Triangle

△S' = Special Small Triangle

TABLE 5 HOFFMAN TEST RESULTS

DOT/TSC SPECIFICATION		
FIXED-ROUTE SUBSYSTEM LEVEL	TEST RESULTS	EDITED DATA RESULTS***
300' - 95%	107	--
450' - 99.5%	156	--
SYSTEM LEVEL		
300' - 95%	105	--
450' - 99.5%	188	--
TIMEPOINT		
15 sec - 95%	11	5*
60 sec - 99.5%	24	8*
RANDOM-ROUTE SUBSYSTEM LEVEL		
300' - 95%	242	--
450' - 99.5%	461	--
SYSTEM LEVEL		
300' - 95%	282	--
450' - 99.5%	464	367**
COVERAGE		
FIXED ROUTE 99.5%	154	--
450' - MAX	312	154**
RANDOM ROUTE 99.5%	367	--
450' - MAX	466	367**

NOTE: *Software fix to properly account for stopped bus.

**Data editing - reference-data acquisition problems.

***See Section 4.1 for definition of "edited."

4.5 TELEDYNE TEST RESULTS

Table 6 presents the test results for the Teledyne Loran-C augmented location subsystem. The first column represents overall test results. The column marked "augmentor problem" shows results of test runs at below freezing temperatures which revealed timing problems in the augmentors that were subsequently corrected by circuit board modification. Subsequent data collection runs were impacted by low voltage output of the auxiliary A-C generator. These results are presented in the "Low-Voltage Problem" column. The "No Voltage-Problem" column shows test results after correction of augmentor and low-voltage problem. The "Loran Only" column presents results from special test runs in a low-rise (suburban) area without signpost augmentation. The "Edited Data" column presents results that could be obtained if the software were modified to improve map matching. Data were also edited to remove those affected by the low A-C generator voltage problem and when the vehicle stopped at timepoints.

TABLE 6 TELEDYNE TEST RESULTS

DOT/TSC SPECIFICATION FIXED-ROUTE	TEST RESULTS	AUGMENTOR PROBLEM	LOW-VOLT PROBLEM	NO VOLT-PROBLEM	LORAN ONLY	EDITED**** DATA
SUBSYSTEM LEVEL						
300' - 95%	352.8	318.6	1269	303.3	325.3	303**
450' - 99.5%	4.9M	1457.6	4.9M	5186.6	375.6	1457**
SYSTEM LEVEL						
300' - 95%	326	269.4	1113	291	--	291
450' - 99.5%	4.9M	787.4	4.9M	383	--	383
TIMEPOINT						
15 sec - 95%	33	47	32	26	--	8***
60 sec - 99.5%	47	65	49	42	--	16***
RANDOM-ROUTE SUBSYSTEM LEVEL						
300' - 95%	358.5	--	--	--	--	358
450' - 99.5%	1222.9	--	--	--	--	1222
SYSTEM LEVEL						
300' - 95%	752.5	--	--	--	--	325-472*
450' - 99.5%	1293	--	--	--	--	375-819*
COVERAGE						
FIXED ROUTE 99.5%	521	--	--	--	--	450
450' - MAX	--	--	--	--	--	
RANDOM ROUTE 99.5%	521	--	--	--	--	450
450' - MAX	--	--	--	--	--	--

NOTE: *Software modification for improved map matching

**Edited - reflects data after correction of low-voltage problem

***Data taken when vehicle stopped was eliminated

****See Section 4.1 for definition of "edited"

5. REFERENCES

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2. Hazeltine Corporation, "Field Testing of a Pulse Trilateration Vehicle Location System in Philadelphia," prepared for DOT/TSC, April 1977.

3. Hoffman Information Identification, Inc., "A Comprehensive Field Test and Evaluation of an Electronic Signpost AVM System," prepared for DOT/TSC, March 1977.

4. Teledyne Systems Company, "Loran Automatic Vehicle Monitoring System," Phase I Final Report, prepared for DOT/TSC, March 1977.

5. Ludwick, J.S., "Automatic Vehicle Monitoring (AVM) System Urban Experiment Test Plan," MITRE Corporation, WP-7859, July 8, 1971.

6. Request for Proposal No. TSC/432-0017-RN, DOT/Transportation Systems Center, July 24, 1975.

Note: Reference Nos. 1,2,3, and 4 are in preparation as technical reports. See Appendix B for excerpts from RFP (Reference 6).

APPENDIX A

BASIS OF AVM PERFORMANCE SPECIFICATION

A.1 AVM BENEFITS

For the multiuser Automatic Vehicle Monitor system development, performance specifications for the location subsystem are based on AVM functional requirements in bus-transit and police operations. Benefit studies in the literature (A1, A2) have postulated that the major bus-transit improvements would be due to the following AVM functions:

1. Minimization of headway variance on short-headway (10 minutes or less) bus-routes by utilizing the central-control capabilities of an AVM system. Such minimization permits significant improvement in the level of service or, conversely, permits the maintenance of the before-AVM level of service (as measured in terms of average waiting times for patrons) with fewer buses.

2. Automatic collection of fleet-operational performance data, for example, accurate and complete measurements of running times (as a function of time, passenger loading, and other conditions) between major stops or "time points" on bus routes. Such data are otherwise difficult and expensive to obtain, but they are essential for devising schedules that optimize service and make efficient use of available buses and drivers.

3. Maintenance of schedules on long-headway (>10 minutes) routes by utilizing the automatic indication of actual position versus scheduled position at every point on a route. Such indication permits improvement in reliability of service--buses would never be early and rarely late.

4. Improvement of driver security and passenger safety by the coupling of a priority "silent alarm" signal into the AVM communications subsystem. When the alarm is activated by the driver, emergency aid can immediately be dispatched to the exact location of the bus.

For AVM use in police operations, the major improvements postulated are

5. Automatic dispatch of the nearest available patrol car to the scene of an emergency call. This dispatch capability permits shortening of response times or, conversely, permits a reduction in the total number of patrol cars required to maintain the before-AVM average response times.

6. Improvement in officer security with a "silent alarm" switch which permits the immediate dispatch of aid to the exact location of an officer in trouble.

For AVM use in taxicab operations, the major improvements postulated are:

7. Automatic dispatch of the nearest available taxi to a telephoned request. Such capability permits reduction in patron wait times and also permits the reduction in "deadhead" or non-revenue miles--a major economic factor in taxi operations.

8. Improvement in driver security with a driver-actuated "silent alarm" which permits immediate dispatch of aid to the exact location of the taxi--a significant improvement for the inherently vulnerable cab driver in high-crime areas.

A.2 AVM PERFORMANCE DATA

Little experimental work has been performed to demonstrate or quantify any of the postulated improvements, much less establish the degree of improvement as a function of AVM system capability (e.g., accuracy of location or fineness of system coverage). Many of the experimental AVM deployments over the past several years have been so severely hampered by hardware or design problems that very few data on operational improvements were obtained (A3, A4). Other trial deployments, notably the Boeing Company's Police-Dispatch AVM in St. Louis, MO, have shown improvements for patrol

car dispatch. However, a recent assessment (A5) of this system reports that initial test data are inconclusive with regard to response-time reduction caused by the AVM. Of several European AVM deployments for fixed-route transit, those in Hamburg and Zurich are successful in improving service reliability. At last report (A4), these systems were being upgraded and systematic data on operational improvements were not yet available.

A.3 ACCURACY REQUIRED FOR POLICE DISPATCH

The paucity of experimental data makes it necessary to rely, almost exclusively, on analytical models for establishing an AVM performance specification. In these models, engineering performance levels (such as accuracy of location) are equated to the level of benefits obtainable. For example, Larson (A5), using a model based on the St. Louis police patrol operations, calculates that a location accuracy of 933 feet is required to effect mean travel time reductions; however, other functions such as coordinating a chase, sealing off an area, or quickly locating an officer in trouble require an accuracy of approximately 220 feet--based on the average length of a city block in St. Louis. In another analysis, Doering (A6) shows that with an accuracy of 800 feet an AVM-dispatched fleet of 34 patrol vehicles can provide an average response time equal to that of a non-AVM system of 35.8 vehicles. Hansen (A7) has extrapolated Doering's results to show an AVM accuracy of 0 feet would permit fleet reductions of 8 to 10% while still maintaining the same average response time; on the other hand, an accuracy greater than 1500 feet would permit no reductions.

A.4 ACCURACY REQUIRED IN BUS-TRANSIT

For bus transit, automatic collection of run-time data for preparing schedules and control of buses on close headway routes for minimization of headway variance place the most stringent requirements on location accuracy. Unlike police dispatch, there is little literature on the analysis of AVM in bus operations. In some work done on assessing the requirements of AVM automatic

data-collection, Bruce (A8) shows that time-of-passage at "time points" must be measured to an accuracy of $\pm$ 30 seconds in order that the resulting new schedules provide significant benefits in terms of optimizing vehicle usage and drivers' paid-time. He also shows that for purposes of monitoring schedule adherence the 95th percentile error should be 15 seconds or less to provide dispatchers an adequate degree of confidence in the system.

Although the inherent headway instability on close-headway routes or the tendency for buses to "bunch" is a common phenomenon, effective counter measures or controls are very difficult to implement. With AVM, a central dispatcher (or computer system) would have a dynamic overview of a whole route and, based on this information, could issue instructions to individual buses to control their spacing on the route. There are many possible control actions but there is little empirical or analytical evidence on which ones or which combinations would be most effective (A9). Two important control concepts, as made practicable with AVM, are those in which

> Buses are constrained to never leaving any stop on the route ahead of schedule. Such control action is made possible by the continuous in-vehicle display of schedule deviation (for all points on the route). Some analytic evidence for the effectiveness of this control action has been presented by Cohn (A10).
>
> Traffic lights are controlled (e.g., by signals from buses) such that appropriate (e.g., "late buses as identified by AVM) buses are given priority thereby increasing average speeds and decreasing headway variances.

The actual development of these and other route control techniques as well as their evaluation awaits a systematic experimental program involving a suitable deployment of a working AVM system. Meanwhile, an indication of the benefit to be gained from a headway-control system is shown in Figure A-1. In this figure, the number of buses required to maintain a constant level-of-service,

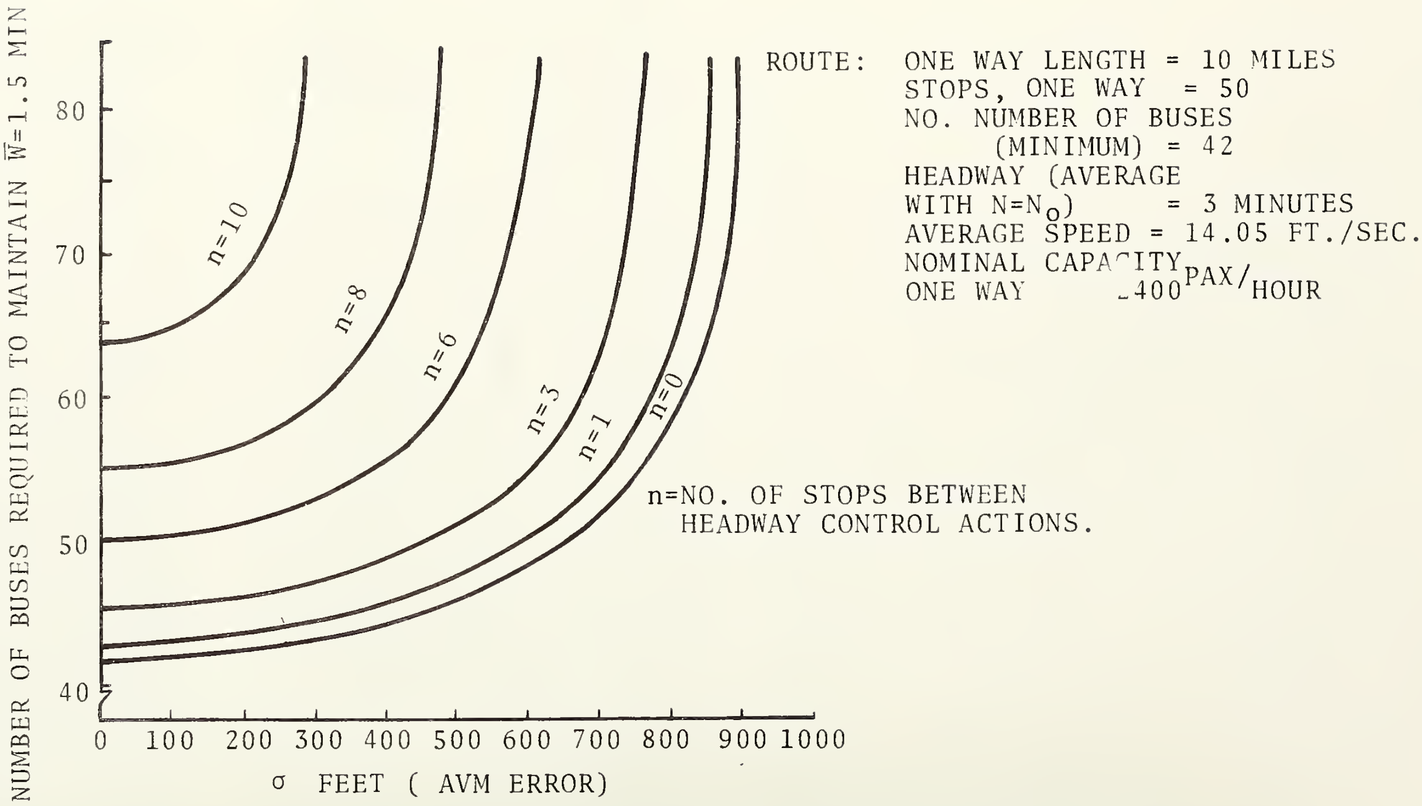

FIGURE A-1. NUMBER OF BUSES REQUIRED TO MAINTAIN SAME LEVEL OF SERVICE: AVERAGE WAIT TIME = 1.5 MINUTES

corresponding to an average wait-time of 1.5 minutes, is shown versus the accuracy to which scheduled position can be corrected and the frequency of control actions which correct the position of the bus to that accuracy. The figure represents a simple model (A-11) of operations on a close-headway route of the following characteristics:

One-way length = 10 miles

Stops, one way = 50

Average speed = 9.6 mph

Average headway = 3 minutes.

The minimum number of buses on the route to maintain average headways ($\bar{h}$), of three minutes is 42. However, to keep the desired average wait time ($\bar{W}$) at 1/2 the headway, more buses are required depending on the statistical variance in the headways. Empirical evidence (A-11) shows that headway variance grows linearly with distance from the last control point on the route (e.g., from a point at which buses are dispatched at regular intervals). For the figure, the variance in headway was taken to be

$$\check{h} \approx \frac{2\sigma^2}{\bar{v}^2} + kn$$

in which

σ^2 = variance from the ideal position of bus after a control action has been taken

$\bar{v}$ = average speed on the route

n = number of stops from the last control action

k = empirical factor

$\sim$ 0.2 min^2 (A-11).

Also, the average wait time was calculated as

$$\bar{W} = \frac{\bar{h}}{2} + \frac{\check{h}}{2\bar{h}}$$

For the figure, it is assumed that after a control action is taken that the variance (σ^2) from the ideal position of the bus is reduced to the minimum variance afforded of the AVM system information. In other words, whatever the control mechanism is, it is sufficiently effective to adjust the position of the bus to the accuracy of the AVM-supplied data. For example, if the 95th percentile accuracy of the AVM location subsystem is 300 ft. ($\sigma \approx 150$ ft.), and the control action is taken every six stops ($n=6$), then the number of buses required to maintain $\overline{W} = 1.5$ minutes is about 51.

Although the figure is based on a very simple model, it demonstrates the very large potential benefit in terms of buses saved (while keeping a desired level-of-service) if an accurate AVM system is coupled with an effective control mechanism.

A.5 PERFORMANCE SPECIFICATION

Based on the analytical work in the literature and what was considered to be within the state-of-the-art of a range of competitive location subsystem technologies, the major items in the DOT/TSC performance specification were

> 300 feet, 95th percentile for location accuracy on fixed and random routes
>
> 15 seconds, 95th percentile for time-of-passage accuracy on fixed routes.

These performance levels were those, then, that have potential for giving significant benefits in AVM applications.

A.6 REFERENCES

A1. Reed, H.D., et al., "A Study of the Costs and Benefits Associated with AVM," Report No. UMTA-MA-06-0041-77-1, DOT/TSC, Feb. 1977.

A2. The Institute of Public Administration and Teknekron, Inc., "An Analytic and Experimental Evaluation of Alternative Methods for Automatic Vehicle Monitoring," submitted to the Chicago Transit Authority and the U.S. Dept. of Transportation, July 1968.

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A11. Blood, B., "Headway Control and Average Waiting Time on Urban Bus Routes," material on file, DOT/TSC.

APPENDIX B

STATEMENT OF THE MULTIUSER AVM LOCATION SUBSYSTEM PERFORMANCE SPECIFICATION

As excerpted from the "Multiuser Automatic Vehicle Monitor System: Request for Proposal (TSC-432-0017-RN)," issued by the Transportation Systems Center, July 1975, the complete statement of the location subsystem performance specification is given below. This specification was the official standard of performance for the four location subsystems tested in Philadelphia.

EXCERPT FROM RFP TSC-432-0017-RN

"3.2 AVM ACCURACY

Location accuracy is specified at two AVM system levels:

1. Location Subsystem--The L.S., independent of other system elements, hsall satisfy the accuracy requirements in 3.2.1.

2. AVM System--Vehicle position indications and time-of-passage determinations shall satisfy the accuracy requirements in 3.2.2.1, 3.2.2.2 and 3.2.2.3 below.

3.2.1 <u>Location Subsystem (L.S.) Accuracy Specification</u>

For a single AVM-equipped vehicle at any given instant, L.S. error is the radial distance between the true position and the L.S. measured position. The L.S. error shall be

Less than 300 feet for 95% of all possible true vehicle-locations

Less than 450 feet for 99.5% of all possible true vehicle-locations

and, in addition, for the L.S. measurements of true locations on any 0.1 mile segment of any possible travelway, the average of the corresponding L.S. errors shall not exceed 450 feet. The above specifications are applicable under the following conditions:

"Possible true locations comprise all geographic points on all travelways in the specified area of AVM coverage as well as on any separately specified routes of AVM coverage.

The vehicle is operating at any speed in the range 0 to 100 m.p.h.

Environmental conditions are within the specified range.

The telemetry (e.g., from vehicle to central) is "perfect," i.e., all L.S. data gathered on the vehicle (and/or at auxiliary receiving sites) are transferred without alteration to the point of processing.

3.2.2 AVM System Accuracy Specification

3.2.2.1 Fixed-Route Vehicles - For all AVM-equipped vehicles operating on fixed routes during any statistically significant period of time (i.e., at least the length of one full operational day for the system), at least 95% of all such position indications shall be in error by less than 450 feet. This fixed-route system error is the straight-line distance between the true position of a vehicle at a given time and system-indicated position (for the same time) as presented to the dispatcher or stored for subsequent off-line use. Note that the system-level error includes effects (e.g., polling procedures) which degrade the inherent accruacy of the L.S. measurements, but also includes effects (e.g., position extrapolation) which enhance the accuracy or compensate for the effects of error sources.

This specification is applicable under the following conditions

Vehicles are operating on all of the routes specified

Vehicles are operating at speeds in the normal range experienced in urban bus transit

Environmental conditions are within the specified range.

"3.2.2.2 Random-Route Vehicles - For all AVM-equipped vehicles operating on random routes in the AVM-coverage area during any statistically significant period (i.e., at least the length of one operational day for the system), at least 95% of all position indications of all random-route vehicles shall be in error by less than 300 feet, and at least 99.5% of all such position indications shall be in error by less than 450 feet. The random-route system error is the radial distance between the true position of a vehicle at a given time and the system-indicated position (for the same time) as presented to the dispatcher or stored for subsequent off-line use. Note that the system-level error includes system effects which degrade the inherent accuracy of the L.S. measurements as well as system capabilities that enhance the accuracy or compensate for the effects of error sources.

This specification is applicable under the following conditions

Vehicles are operating on any travelway in the specified area

Vehicles are operating at speeds in the normal range experienced in urban traffic

Environmental conditions are within the specified range.

3.2.2.3 Fixed-Route Schedule Monitoring (Time-of-Passage) Accuracy - For fixed-route transit vehicles the AVM system shall have the capability for the determination of

schedule deviations
running times
differences between scheduled and actual start times for runs
differences between scheduled and actual layover times.

For all designated time points on all specified routes, the times of bus passage, as determined by the AVM system, shall be accurate to ± 15 seconds for 95% of all such determinations and ± 60 seconds for 99.5% of all such determinations (considering a statistically significant period of time--at least one full operational

"day for the system). Derived times and time periods (those identified above and others), as presented to the dispatcher or stored for off-line use, shall be fully consistent with the times of passage specification; e.g., indicated schedule deviations shall be accurate to ± 15 seconds for 95% of all such indications. As this is a system-level specification, all applicable sources of error and data enhancements are included.

The above specification is applicable under the following conditions:

All AVM-equipped buses are operating on all specified routes.

Bus trajectories (i.e., detailed time/position histories) are those typical of urban transit bus operation on fixed routes.

Time points are established prior to system operation, but may be located at any points along the routes.

Time-of-passage knowledge also implies time of departure knowledge for those events at which the bus has stopped at a time point."

APPENDIX C

LOCATION SUBSYSTEM TECHNIQUES

C.1 CATEGORIES

Techniques for automatically locating land vehicles may be classified in three general categories:

1. Proximity or signpost
2. Radio-Frequency (RF) Multilateration (or, most often, Trilateration)
3. Dead-Reckoning

Each of these general techniques has unique economic (C1) and performance attributes in different deployments. For example, proximity systems require a significant amount of wayside hardware, particularly in providing coverage for random-route vehicles; RF multilateration systems require relatively sophisticated electronics and data processing; and dead-reckoning systems require auxiliary means for providing initial position and then for frequent corrections to bound the errors.

C.2 PROXIMITY

In proximity systems, autonomous "signposts" located at intervals along travelways present their coded geographic identity to passing vehicles. There is a large variety of signpost types starting with radio transmitters which continuously broadcast their geographic code to be received by an AVM-equipped vehicle that is within some preset range--ordinarily the dimensions of a street intersection or 100 feet or so. Other signpost types include coded placards that are automatically read by optical or microwave scanners on the vehicles. (There is also an "inverted" type of proximity system in which scanners on the wayside read coded signs on the vehicles. In this scheme the event of a particular vehicle passing is transmitted from the scanner site to a central tracking station.) A general distinction between signpost types is the

precision of location inherent to each; for example, the radio broad-field type gives a precision of 100 feet or so whereas an optical scanner type will give sharp precision of a few inches. This distinction can be very important for system costs as well as performance.

For random-route vehicle tracking, signposts would need to be installed at least at every other intersection--assuming an ideal rectangular street pattern. At these intersections, one broad-field signpost would be needed, whereas up to four of the sharp-field signposts would be needed to cover the possible vehicle manuevers (i.e., turns). Since vehicle position is known only at the signpost and yet it is desirable to use the minimum number of installations--i.e., at every other intersection--most proximity AVM concepts include the use of an odometer to provide incremental distance measurement between signpost installations and thereby achieve accuracy specifications (e.g., $\pm$ 300 feet). In one unique broad-field signpost system, the use of the odometer is obviated by adjusting the radiation fields of adjacent signposts to overlap. By measurement of relative field strengths, position between the signposts is obtained. Field strength decreases approximately linearly with distance from the signpost.

C.3 RF MULTILATERATION

There are many radio navigation concepts that utilize time-of-arrival or phase differences of synchronized RF signals from (or to) three or more transmitters (or receivers) located at known geographic points. With assumption of straight-line transmission paths, these time or phase differences are used to calculate position by trilateration. Two of these techniques that are particularly applicable to land vehicles are described below.

<u>Loran-C</u>--The Long Range Navigation Grid maintained by the U.S. Coast Guard is used for navigation of ships in the coastal confluence. By 1978 most coastal regions of the U.S. will be covered by this grid; and it is anticipated, with the additon of a few necessary transmitters, all of the continental U.S. can be covered

in the next few years. Loran-C provides position at a ship, aircraft or land vehicle by transmitting pulsed 100 KHz carriers from three geographically separated transmitters. Two of the transmitters are time-slaved to the third so that the time differences of pulse arrivals can be used to locate the vehicle.

Theoretically, constant time difference of pulse arrivals from any pair of stations defines a hyperbola on the surface of the earth. The crossing of two such hyperbolas gives the position fix. For ships, hyperbolas of constant time differences are overlaid on navigation charts. On land, however, variations in conductivity over transmission paths from the transmitters may not permit the construction of geometrically-true hyperbolas. It is empirically known that measured time-differences are stable (i.e., continuously the same at a given location); however, the grid needs to be calibrated for land use--the more the distortion in the hyperbolas, the more or denser the calibration points needed to provide a given accuracy.

Pulse Trilateration--A network, over an entire AVM coverage area, of receiving stations--separated, each from the other by a distance determined by power levels and other factors--receive sharp rise-time pulses on high frequency carrier signals from tracked vehicles. Each vehicle emits its pulse followed by a message code in an assigned time slot. The times of pulse-arrival at the receiving sites are established and then relayed by wire link to a central computer. Here the vehicle position is calculated by a trilateration algorithm using the pulse-arrival times at three of the receivers best situated to determine that vehicle's position. (The selection of the three receivers to be used may be based on a priori knowledge of a particular vehicle's operational area or knowledge of its last position.) At carrier frequencies of 1000 MHz, it is estimated that the average separation of the receiver sites will be six miles in urban areas. This is a significant parameter in the system cost equation and its empirical determination is quite important.

C.4 DEAD-RECKONING

A dead-reckoning location technique is generally characterized by providing position information without reference to external signals. An example is the Boeing Company's Police-Dispatch system deployed in St. Louis, MO (C2). The system utilizes a magnetic heading indicator and a precision odometer to track vehicle position. As with all dead-reckoning schemes, position errors are cumulative and an auxiliary method is incorporated to provide the position of a starting point and thereafter at frequent intervals to keep the error within specification. For the starting position, the vehicle operator transmits his position to a central computer; thereafter, the tracking is accomplished automatically by transmitting heading and distance-increments to the central computer at very frequent intervals (about 1.2 seconds). These data are used to update the vehicle position on a very accurate "map" stored in the computer memory. When the compass indicates that a turn has been made, the computer automatically "places" the vehicle on the nearest street location compatible with the change in heading. By "placing" the vehicle on the nearest new street, any accumulated position error is automatically zeroed. The scheme works best for a vehicle that makes frequent turns.

C.5 REFERENCES

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C2. Larson, R.C., et al., "Evaluation of an Implemented AVM System: Phase I," Report Prepared for the Law Enforcement Assistance Administration, Public System Evaluation, Inc., Cambridge, MA, May 1976.

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